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Green hydrogen revolution: Mapping G20 nations' policies and geopolitical strategies in the net-zero emission era

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Abstract

The transition towards net-zero carbon emissions is increasingly defined by the emergence of green hydrogen as a pivotal technology. This review article explores the policies and geopolitical strategies of G20 nations in navigating the Green Hydrogen Revolution. Green hydrogen, produced through renewable energy-powered electrolysis, promises to decarbonize sectors traditionally reliant on fossil fuels. This article examines how G20 countries are positioning themselves within this transformative energy landscape, emphasizing policy frameworks, investment trends, and technological advancements. Geopolitical implications, including international cooperation, competition, and energy security considerations, are analyzed to understand the evolving global dynamics of energy transition. By mapping out the diverse approaches of G20 nations, this article provides insights into the complex interplay between domestic policies and global energy strategies in achieving sustainable development goals and addressing climate change challenges in the 21st century.

This article is categorized under:

Climate and Environment > Net Zero Planning and Decarbonization

Policy and Economics > Energy Transitions

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KEYWORDS

electrolyzer, G20 nations, green hydrogen, hydrogen economy, policies

1 | INTRODUCTION

The Paris Climate Agreement, adopted by the parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, was signed by 197 nations and put into force in November 2016. This first global climate change accord intends to reduce greenhouse gas emissions to keep global average temperatures below 2°C and achieve NetZero status by 2050 (UNFCCC, 2018). After signing, nations worldwide began efforts to reduce all anthropogenic emissions contributing to rising temperatures and climate change, primarily from electricity and heat generation, transportation, manufacturing, and construction, depending on the nation. As a result of the accordance, nations across the world have boosted their renewable energy (RE) production through solar and wind (Lacal Arantegui & Jäger-Waldau, 2018; Singh et al., 2023), along with fossil fuels to meet their nation's energy demand and to reduce carbon emissions. The signed nations have set an aggregate emissions reduction target by 2030, and as a result, nations have split policies to cover emissions in all sectors (Steffen, 2021).

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Advancements in solar and wind energy in recent decades have started to help decarbonize economies since the decreasing cost of unit renewable power generation is almost comparable to the price of coal-generated electricity globally (IRENA, 2021), resulting in a surge of renewable power generation (Luderer et al., 2022). However, the abundance of sunlight and wind determine the amount of electricity generated by these technologies (Tong et al., 2021); additionally, the capacity factors of these energies are much lower (Boretti, 2019a; Boretti, 2019b) when compared with coal-fired or nuclear-based power plants, which require a fossil-fuel-based or nuclear power plant to meet the ever-growing electricity demand. The growing economies require an uninterrupted power supply to thrive, forcing them to rely on affordable high-capacity-factor energies for their requirement (Rahman, 2020; Raihan et al., 2022; Saint Akadiri et al., 2020).

Hydrogen can replace fossil fuels and be a significant contributor to curbing climate change in most polluting sectors, as it is a practical, scalable, renewable, and low-emission energy source. It stands out as a versatile fuel due to its many production techniques and applications equivalent to fossil fuels (Castelvecchi, 2022). Furthermore, hydrogen functions as an intermediate energy storage system, converting RE into hydrogen and back into RE without interruption (Mayyas et al., 2020). The recent Russian invasion of Ukraine has caused turmoil in global energy markets, resulting in abrupt jumps in energy prices that have sent economic shockwaves around the world. Climate change has increased the focus on energy security for the net oil-importing nations, forcing them towards diversified, sustainable, and RE transition at affordable prices, also resulting in a spike of renewable and green hydrogen policies and investments worldwide (Colgan et al., 2023; Yagi & Managi, 2023).

In this review, we try to adequately map the governments' policies and geopolitical strategies of G20 nations by dividing them into developing, developed, oil-importing, and oil-exporting nations as the transition threatens a few oil-exporting nations while benefiting oil-importing nations. Policies shape a nation's capability to emerge as a leader in the hydrogen transition. These nations will determine the future of green hydrogen in the coming years to achieve NetZero. The G20 nations are the best group of nations to track the policies, geopolitics, and strategies as they collectively represent 65% of the world's population, 79% of the world's trade, 84% of the world's economy, more than three-quarters of the energy demand, 85% of the global energy consumption, and 79% of the world's carbon emissions (Ram et al., 2018; World Economic Forum, 2022). The G20 nations have strong and rising industrial and service-based economies with a shared aim of sustainability. Even though the policies and paths differ due to geographic and political scenarios, all the member nations' policies represent lower-cost renewable technology that benefits society and the world.

2 | UNDERSTANDING GREEN HYDROGEN

Since its recognition as a feasible future low-emission energy source, nations worldwide started investing in hydrogen in the endeavor to become pioneers of the latest renewable technology to emerge as an energy-independent nation and simultaneously reduce the carbon footprint of their economy (Cox, 1976; Ohta & Abe, 1985; Peraldo Bicelli, 1986). The US started to support the research of hydrogen as an alternative fuel during the Gulf oil crisis (Adelman, 1990; Gately et al., 1986), but due to a considerable difference in the techno-economic and feasibility analysis, the governments paused the extensive funding for the research as the crude oil prices returned to normal (Bockris, 1981; O'N Bockris & Veziroğlu, 1983). Hydrogen carries a higher calorific value of 120–140 MJ/kg after Uranium, resulting in a more excellent energy-to-weight ratio when compared with standard fossil fuels. Moreover, hydrogen does not emit any radioactive waste or carbon emissions, making it an attractive, sustainable fuel as it yields water as a by-product. Besides playing a significant role in decarbonizing, it is ideal for a forthcoming paradigm shift towards RE.

Currently, the majority of hydrogen produced globally is produced using the steam methane reforming (SMR) process (Gray Hydrogen) is utilized on-site by the petrochemical and chemical industries for the Fischer-Tropsch Gas-To-Liquid products, ammonia and urea (Abdin et al., 2020). The main disadvantage of this process is that it produces CO_2 as a by-product. Suppose this CO_2 gets captured and stored during hydrogen. In that case, the process is known as blue hydrogen, which is substantially more sustainable than gray hydrogen since no direct carbon emissions are discharged into the atmosphere (Hermesmann & Müller, 2022; Saha et al., 2024). On the other hand, the carbon footprint of hydrogen produced through electrolysis is determined by the source of electricity generation from coal, natural gas, nuclear power, or RE. Compared with the SMR process, CO_2 emissions of electrolysis are insignificant when integrated with RE, making it a more suitable process to manufacture hydrogen for nations worldwide, aiming to meet the NetZero emissions target.

A key benefit of green hydrogen is that it merely requires an electrolyzer with a steady supply of renewable electricity and water, all of which can be easily assembled and carried anywhere in the world, in contrast to conventional fuels such as natural gas, oil, and coal, which either need to be extracted, or imported from other nations, at a dynamic price depending on the seasons, geopolitics, and bilateral relations of the exporting countries. Hydrogen can be generated, stored, and transported to meet energy requirements without trade restrictions. In 2020, global electrolysis capacity was 0.3 GW, accounting for 0.03% of total hydrogen production. Europe (40%), Canada (9%), and China (8%) had the most capacity. However, cumulative installed electrolysis capacity is expanding at an exponential rate. After more than doubling in just 2 years from 2019 to 2021 (from 242 to 513 MW), it was forecast in September 2022 to nearly triple (1398 MW) within a year by the end of 2023. By 2050, the IEA's global net zero scenarios forecast a fivefold increase in worldwide hydrogen production (IEA, 2021b).

Electrolyzers are chemical devices that efficiently split water into hydrogen and oxygen using electricity without carbon emissions. This is vital for green hydrogen generation as these systems run primarily independently. There are different types of electrolyzers, including alkaline electrolyzers (ALK), proton exchange membrane electrolyzers (PEM), anion exchange membrane electrolyzers (AEM), and solid oxide electrolyzers (SOEC) (Amini Horri & Ozcan, 2024; Sharshir et al., 2023; Shiva Kumar & Lim, 2022). The ALK dominated 61% of installed capacity in 2020, while PEM had a 31% share. As shown in Table 2, the current green hydrogen production projects are predominately dominated by the ALK and PEM electrolyzers due to economic viability in medium to large-scale projects, facile technology, portability, scalability, ease of maintenance, and policy regulations. The remaining capacity of unspecified electrolyzer technology and SOECs (IEA, 2021b), as the SOECs operate at higher temperatures, requires an additional heat supply source to increase the system's efficiency. Solar PV and wind are the most used RE technologies which are integrated with these electrolyzers for power supply as these electrolyzer technologies can be installed at less capital expenditure based on the availability of land and RE resources; in case of the hydropower, the nation's geographic location plays a vital role in the construction of the hydropower projects.

In many nations, pilot projects have been started to demonstrate hydrogen production, storage, transportation, and applications in all the major polluting sectors, including power generation, transportation, heavy industries, manufacturing, and cement. In the petroleum sector, refining oil requires vast amounts of hydrogen produced by the SMR process due to its economic viability. As the shipping costs of hydrogen still amount to 2–3 USD/kg, in the present situation, the green hydrogen is to be transported at a shorter distance from the production site (IRENA, 2022). Meanwhile, nations and heavy industries have begun attempting to manufacture hydrogen using electrolysis to decarbonize their sector. The SMR process is still widely employed due to the cost of RE and the capital cost of the electrolyzer, making it more difficult for industries to transition towards green hydrogen (Espegren et al., 2021; Nhuchhen et al., 2022; Öhman et al., 2022).

3 | POLICIES AND INITIATIVES IN G20 NATIONS

Following the Paris Agreement, the G20 nations began to develop policies and roadmaps to reduce carbon emissions in hard-to-abate sectors. As shown in Table 1, most G20 nations have published their green hydrogen policies, focusing on all industries with higher carbon emissions and financing to promote research and pilot projects in their countries. The global green hydrogen initiatives firmly commit to achieving net-zero emissions and promoting sustainable energy sources. Argentina, Australia, and the European Union (EU) have set ambitious targets for green hydrogen production and export. Argentina aims to produce 5 million tons (Mt) by 2050 using 55 GW of renewables, while Australia seeks to leverage its natural resources to achieve NetZero by 2050, supported by a $14 billion investment. The EU plans to produce 10 Mt annually with 40 GW of electrolyzer capacity by 2030, backed by an impressive $155 billion investment. Emerging economies like Brazil, India, and South Africa are also making strides, with Brazil focusing on low-carbon hydrogen production and India aiming to produce 5 Mt by 2030. Notably, Japan and South Korea are integrating hydrogen into various sectors, including power generation, heating, and transportation, with substantial investments of $18.2 billion and $16.26 billion, respectively. The United States is determined to reduce green hydrogen costs to $2/kg by 2030, enhancing domestic and commercial demand. These initiatives, spanning diverse energy sources such as renewables, fossil fuels, and nuclear power, underscore a global transition towards a sustainable, hydrogen-based future.

After analyzing the policies from Table 1 and by dividing the nations as per Table 2, we have divided the G20 nations into four categories: (1) Advanced economies with net oil exports, (2) advanced economies with net oil imports, (3) emerging economies with net oil exports, and (4) emerging economies with Net oil imports. The categorization of

TABLE 1 G20 nation's hydrogen strategies, roadmaps, and policies.

Nations	Availability of green hydrogen initiatives[a]	Published in year	Objectives of the initiative	Other energy sources in focus	Proposed usage of hydrogen in sectors	Investments	References
Argentina	β	2023	By 2050, the nation plans to produce 5 Mt of green hydrogen at $1.40/kg using 30 GW of electrolyzers powered by 55 GW of renewables and export 4 Mt via 2–5 hubs.	Renewables	Industry, transport, export	NA	Secretariat for Strategic Affairs (2023)
Australia	β	2019	Australia aims to use its natural resources to produce, export, and utilize green hydrogen to achieve NetZero by 2050.	Fossil and renewables	Industry, heating, transport, export	14 billion USD	Department of Industry (2019)
Brazil	◇	NA	In 2023, the nation launched a plan to increase low-carbon hydrogen production by 2025 and achieve cost-competitiveness by 2030. A hydrogen framework is in progress.	Renewables	—	European Union to invest 2 billion Euros.	Ministério de Minas e Energia (n.d.)
Canada	β	2020	The vision of the nation is to reduce CO_2 emissions annually by using hydrogen for at least 30% of Canada's energy requirement and also to in 5 million FCEV by 2050	Fossil, nuclear, and renewables	Heating, Industry, transport, export	1.09 billion USD	Canada (2024)
China	Δ	2022	The Chinese plans to produce around 0.1–0.2 million tons of hydrogen annually and have about 50,000 FCEV by 2025.	Fossil, nuclear, renewables	Industry, transportation, export	NA	Páng bó (n.d.)
France	β	2020	The French are targeting a 10 GW capacity of green hydrogen production by 2035 to replace fossil	Nuclear, renewables	Industry, transport, export	7.6 billion USD	Pompili and Le Maire (2020)

TABLE 1 (Continued)

Nations	Availability of green hydrogen initiatives[a]	Published in year	Objectives of the initiative	Other energy sources in focus	Proposed usage of hydrogen in sectors	Investments	References
			fuels in mobility and industries.				
Germany	β	2020	The Dutch targets to have a 5 GW electrolyzer capacity by 2030 with an expectation of demand reaching up to 95–135 TWh	Renewables	Industry, transport, heating	22.83 billion USD by 2026	BMWK-Federal Ministry for Economic Affairs and Climate (2022)
India	Δ	2022	India targets to be self-reliant in green hydrogen and be a hydrogen exporter by producing at least 5 million metric tons of hydrogen by 2030 in a phased manner.	Renewable, fossil fuels and nuclear	Industry, transport, export, heating and power generation	2.6 billion USD by 2030	Ministry of New and Renewable Energy India (2023)
Indonesia	☒	NA	The nation intends to be a green hydrogen hub after 2030 as it invests in green hydrogen technologies.[b]	Biofuels	—	—	Direktorat Jenderal EBTKE—Kementerian ESDM (2023)
Italy	β	2020	By 2030, the nation wants to install 5 GW of electrolyzer capacity and replace 2% of the nation's energy with hydrogen by replacing long-haul trucks with FCEV.	Renewables	Transportation, industry, heating	10.8 billion USD by 2030	Ministero delle Imprese e del Made in Italy (2020)
Japan	Δ	2019	By 2030, the nation wants to use 3 million tons of H_2 and increase to 20 million tons by 2050. It aims to produce hydrogen at 2.49 USD/kg by 2030 and reduce it to 1.42 USD/kg by 2050.	Fossils, renewables and nuclear	Industry, heating, power generation and transport	18.2 billion by 2030	HyResource (2018)
Mexico	⊙	NA	—	—	—	—	—
Russia	Δ	2021	The nation plans to produce 2 million tons of H_2 by 2030,	Fossils, nuclear, and renewables	Export	1.7 billion USD by 2030	OSW Centre for Eastern Studies (2021)

(Continues)

TABLE 1 (Continued)

Nations	Availability of green hydrogen initiatives[a]	Published in year	Objectives of the initiative	Other energy sources in focus	Proposed usage of hydrogen in sectors	Investments	References
			primarily using fossil fuels as feedstock with CCUS.				
Saudi Arabia	◇	NA	—	—	—	—	—
South Africa	Δ	2021	The nation aims to produce 0.5 million tons of H_2 annually, install an electrolyzer capacity of 12 GW by 2030, and increase it to 15 GW by 2040.	Fossil fuels and renewables	Transport industry, power generation, and export	—	Department of Science and Innovation (2021)
South Korea	Δ	2019	The nation aims to produce 5.2 million tons of H_2 per year by 2040 and expects an FCEV of up to 5.9 million, along with 1200 H_2 refueling stations.	Fossils and renewables	Power generation and transportation	16.26 billion USD by 2025	IEA (2020)
Turkey	β	2023	The nations intend to have 2 GW of electrolyzer capacity by 2030, 5 GW by 2035, and 70 GW by 2053, as well as to manufacture hydrogen at <2.4 USD/kg by 2035 and 1.2 USD/kg by 2053.	Fossils and renewables	Power generation, transportation, and industry	—	Climate Policy Database (2023)
United States	β	2021	The United States is determined to reduce the green hydrogen price to 2 USD/kg by 2030 and increase the domestic and commercial demand for green hydrogen in three waves.	Renewables, fossil fuels, and nuclear.	Industry, transport, and power generation	9.5 billion USD	Hydrogen Program (2023)
United Kingdom	β	2021	The nation aims to build 5 GW of electrolyzer capacity by 2030 to replace natural gas	Renewables	Heating, transport, power generation and industry	4 billion USD	Kwasi and Anne-Marie (2021)

TABLE 1 (Continued)

Nations	Availability of green hydrogen initiatives[a]	Published in year	Objectives of the initiative	Other energy sources in focus	Proposed usage of hydrogen in sectors	Investments	References
			for 3 million UK homes, transportation, and industry.				
European Union (EU)	β	2020	The EU plans to produce 10 million tons of H_2 per year with 40 GW electrolyzer capacity by 2030	Renewables and fossil	Industry, mobility	155 billion USD	Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (2020)

Abbreviations: FCEV, fuel cell electric vehicles; NA, not available.
[a]α = Green Hydrogen Policy Available, β = Green Hydrogen Strategy Available, Δ = Green Hydrogen Roadmap Available, ☒ = Policy or Strategy or Roadmap is not available, ⊙ = Policy or Strategy or Roadmap under discussion, ◇ = Policy or Strategy or Roadmap Under Preparation.
[b]Indonesia launched its strategy on 15th December 2023, where the nation hopes to become a hydrogen hub due to its location next to a trade route.

TABLE 2 List of G20 nations with their economic and oil status (Daniel, 2022; IMF, 2023).

S.no.	Nation	Economic status[a]	Oil importing/exporting status[b]
1	Argentina	E&D	NI
2	Australia	A	N-E
3	Brazil	E&D	N-E
4	Canada	A	N-E
5	China	E&D	NI
6	France	A	NI
7	Germany	A	NI
8	India	E&D	NI
9	Indonesia	E&D	N-E
10	Italy	A	NI
11	Japan	A	NI
12	Mexico	E&D	N-E
13	Russia	E&D	N-E
14	Saudi Arabia	E&D	N-E
15	South Africa	E&D	NI
16	South Korea	A	NI
17	Turkey	E&D	NI
18	United Kingdom	A	NI
19	United States	A	N-E
20	European Union	—	—

[a]E&D = Emerging and developing, A = Advanced.
[b]N-E = Net Exporting, NI = Net Importing.

these countries shows similar like-minded nations ready to decarbonize their economies through green hydrogen in the future. These categories also show the common grounds and differences between nations regarding green hydrogen policies, investments, and the de-subsidization of the fossil fuel industry.

The first category includes advanced economies that have net oil exports, such as Australia, Canada, and the United States. These countries also rely on fossil fuels in some capacity to generate electricity and meet other energy needs. These countries are spending heavily on R&D activities to promote the energy transition to hydrogen and other renewable energies, intending to become net zero following national regulations. On the other hand, these nations are still extracting and exporting fossil fuels to other countries. The nations have not mentioned any timeline for quitting the extraction of these fuels altogether.

The second category comprises advanced economies with net oil imports, such as France, Germany, Italy, Japan, South Korea, and the United Kingdom. The European nations in this group have faced an energy crisis during the winters in the last 2 years as a result of the Russian-Ukraine war, forcing them to consider the energy transition as it reduces their reliance on other nations for their energy requirements and provides self-sufficient RE fuels for their countries. Following the nuclear incident 2011, the Japanese government suspended nuclear energy production due to safety concerns. However, the government has resumed nuclear energy production as the nation's pollution levels have increased due to fossil fuel electricity generation (Nakazawa & Tatsumi, 2023). South Korea has also recently transitioned to hydrogen as its primary fuel source, as the country currently imports fossil fuels and nuclear fuel for power generation.

The third category includes Brazil, Indonesia, Mexico, and Saudi Arabia, all of which have yet to create green hydrogen policies since writing this advanced analysis. Brazil has the most significant RE penetration in its energy system of any G20 country, with hydropower accounting for most of it. It has a high potential to become the first NetZeo nation. Russia primarily concentrates on hydrogen production from methane. It exports it to neighboring countries due to its substantial methane reserves and green hydrogen policy, as the government expects that the EU will require massive amounts of hydrogen to become net zero, which is not achievable with Russian hydrogen.

Argentina, China, India, South Africa, and Turkey fall into the fourth category, competing with advanced nations on green hydrogen policy. China and India are rapidly developing their renewable energy capacity in their national grids, with plans to increase their green hydrogen capacity. However, these countries also focus on fossil fuels due to their large populations. South Africa and Turkey are gradually boosting their renewable energy and green hydrogen production capability while continuing to use fossil fuels for their energy requirement.

Most of the G20 nation's green hydrogen strategies have short- and long-term goals to boost green hydrogen production capacity and apply hydrogen as a fuel in highly polluted sectors. These sectors include heavy industries such as steel, cement, refining, and chemical production. In transportation, a few countries, like South Korea, Canada, China, Italy, and the United States, focus on FCEVs to replace conventional vehicles. Decarbonizing heavy transportation sectors like maritime and aviation requires significant investments from both governments and the private sector. Few countries and companies have decided to transition to sustainable alternative fuels in these industries. Two small firms in the United States and Europe have been exploring hydrogen-based electric propulsion for smaller planes, and Airbus has announced its zero-emission plane powered by hydrogen (Airbus, 2021; Universal Hydrogen, 2024; ZeroAvia, 2024).

The main issue with RE is that its output depends on the weather, making it unreliable compared with fossil fuels. However, depending on demand, conventional power plants can be scaled up or reduced based on the demand. If an excess of RE is generated during low demand, the generated energy is wasted. The G20 nations are also researching various options, such as conventional batteries, pumped hydro storage, gravity batteries, and hydrogen for storing the excess RE generated. Given that large-scale hydrogen fuel cells are expensive for energy conversion, the countries focus on small-scale, scalable, portable power units as pilot projects. Studies and background work in other countries remain essential for several G20 nations in many sectors. The production costs of green hydrogen vary considerably based on the regions with RE potential, infrastructure, and capital costs. The areas with abundant RE may turn into green hydrogen exporters selling to the highest-demand regions. As green hydrogen technology is still costly, most G20 countries are forced to rely on traditional energy while gradually incorporating renewables into national electricity grids.

As per the current policies and roadmap laid out by the nations, the use of green hydrogen will be evident in these industries in the future with the help of subsidies and carbon tax similar to the European Union's policy. The European Union's carbon tax policy is forcing its neighboring countries to produce, store, and transport hydrogen to its borders at

a lower carbon footprint, as the union drafted its policy to declare emissions under the Carbon Border Adjustment Mechanism (CBAM) and pay the tax relying on the CBAM certificates (Zhong & Pei, 2024).

Australia, Japan, and South Korea led in 2019, as shown in Figure 1, followed by Canada, France, Germany, Italy, and the EU in 2020. Russia, South Africa, the United States, and the United Kingdom joined in 2021, with China and India in 2022 and Argentina and Turkey in 2023. Brazil, Indonesia, Mexico, and Saudi Arabia are yet to release their policies. China and India are exponentially increasing their RE capacity in their national grids and targets to increase their green hydrogen capacity. Still, these nations are also focusing on fossil fuels as they require vast amounts of energy due to their vast population. South Africa and Turkey are gradually increasing their renewable energy and green hydrogen production capacity by continuing to use fossil fuels. Overall, the nations that import oil are looking forward to green hydrogen as they can reduce the spending on foreign exchange during price shocks in an unavoidable geopolitical situation.

As governments prepare to improve green hydrogen regulations, a few countries, including China, Japan, Germany, Brazil, Australia, the United Kingdom, and France, have already begun to produce hydrogen exclusively through RE; Table 3 depicts the biggest hydrogen production plants that employ electrolyzers with RE. China leads the hydrogen project landscape with significant initiatives like Sinopec–Kuqa (260 MW) and Ningxia Solar Hydrogen Project Phase 2 (150 MW), predominantly using ALK (Alkaline) technology and Solar PV. These projects have substantial production capacities, producing up to 44.1 kt H_2/year. In contrast, smaller projects like RH2 Grapzow in Germany and Sealhyfe in France produce around 0.1 kt H_2/year. While ALK technology is favored for larger projects, Proton Exchange Membrane (PEM) technology is common in smaller, distributed sites such as Air Liquide Becancour in Canada (20 MW) and the Tyseley Energy Park in the United Kingdom (3 MW). Renewable energy sources like onshore wind, seen in Shell China–Zhangjiakou (20 MW) and Energiepark Mainz in Germany (6 MW), and hydropower, used in projects like Wyhlen hydroelectric power plant in Germany (1.3 MW), support these hydrogen initiatives. The development spans from early projects like WindGas Falkenhagen in Germany (2013) to recent ventures in 2023, such as Sinopec–Kuqa and Yanqing Hydrogen Energy Industrial Park in China. This highlights a diverse technological and geographical spread in the global hydrogen project landscape, reflecting various strategies to harness renewable energy for hydrogen production. As China holds the most critical raw materials for green hydrogen production, the nation focuses on becoming the energy transition leader. South Korea has established the world's largest hydrogen fuel cell power plant, with a capacity of 78.96 MW, capable of producing 700 GWh of electricity per year, enough to power up to 250,000 households and supply heat water to 44,000 homes. This plant also serves as an air purifier, sucking 24,000 tons of fine particles from the neighborhood ("World's Largest Hydrogen Fuel Cell Power Plant," Anonymous, 2021).

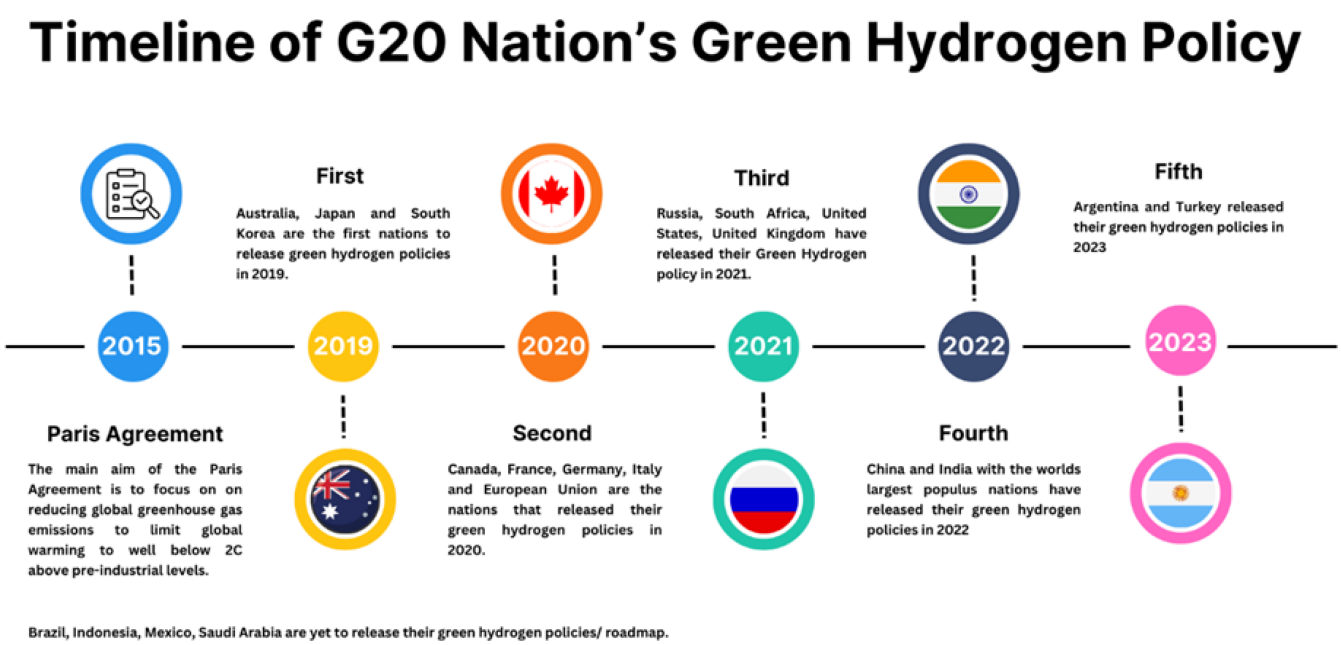

FIGURE 1 Timeline of G20 nation's green hydrogen policy.

TABLE 3 List major green hydrogen production projects in G20 nations with dedicated renewables above 1 MW capacity (IEA, 2023).

				Technology			Normalized capacity		
Sno	Project name	Country	Date online	Electrolyzer type	Type of renewable	Announced size	MWel	Nm^3 H_2/h	kt H_2/y
1	Sinopec–Kuqa	CHN	2023	ALK	Solar PV	260 MW	260	56,522	44.1
2	Ningxia Solar Hydrogen Project, Phase 2	CHN	2021	ALK	Solar PV	150 MW	120	26,087	20.3
3	Three Gorges Corp.'s Inner Mongolia project	CHN	2023	ALK	Solar PV	10 kt H2/y production—15 × 1000 Nm^3/h units	69	15,000	11.7
4	Ningxia Solar Hydrogen Project, Phase 1	CHN	2021	ALK	Solar PV	30 MW	30	6522	5.1
5	Air Liquide Becancour	CAN	2020	PEM	Hydropower	20 MW–8 t H_2/d	20	3846	3
6	Shell China – Zhangjiakou, phase 1	CHN	2022	ALK	Onshore wind	20 MW	20	4348	3.4
7	Fukushima Hydrogen Energy Research Field	JPN	2020	ALK	Solar PV	10 MW	10	2174	1.7
8	Chongli wind-solar Hydrogen Project–second phase	CHN	2022	PEM	Others/ Various	1475 t/y H_2	9.84	1892	1.5
9	Hyper Hydrogen Energy Zhangjiakou Wind Power Hebei–first phase	CHN	2020	ALK	Onshore wind	4.3 t H_2/d	9.3	2013	1.6
10	Wunsiedel Energy Park (Phase 1)	DEU	2022	PEM	Others/ Various	8.8 MW	8.8	1692	1.3
11	Yanqing Hydrogen Energy Industrial Park	CHN	2023	PEM	Unknown	2.8 t H_2/d	6.82	1311	1
12	Energiepark Mainz	DEU	2017	PEM	Onshore wind	6 MW	6	1154	0.9
13	Guangdong Synergy Hydrogen Power Technology Co. 1st phase	CHN	2019	PEM	Unknown	4 MW	4	769	0.6
14	Hebei Jiantou Guyuan wind project–1st phase	CHN	2019	ALK	Onshore wind	10 MW	4	870	0.7
15	Anglo-American Mogalakwena mine	ZAF	2022	ALK	Others/ Various	3.5 MW	3.5	761	0.6
16	Tyseley Energy Park refueling hub Birmingham	GBR	2021	PEM	Others/ Various	3 MW	3	577	0.4
17	EDP Pecem pilot	BRA	2022	PEM	Solar PV	3 MW	3	577	0.4
18	Wuppertal refueling station	DEU	2020	PEM	Others/ Various	2.5 MW–500 m^3 H_2/h	2.5	500	0.4
19	SALCOS–WindH2 Windwasserstoff Salzgitter	DEU	2021	PEM	Onshore wind	2 × 1.25 MW–450 m^3 H_2/h	2.5	481	0.4
20	Zhongyuan Oil Field MW-Scale Renewable P2G, phase 1	CHN	2022	PEM	Others/ Various	4,080,000 Nm^3/y	2.42	466	0.4
21	Wind to Gas Südermarsch	DEU	2019	PEM	Onshore wind	2.4 MW–450 m^3 H_2/h	2.4	450	0.4
22	WindGas Falkenhagen	DEU	2013	ALK		2 MW	2	435	0.3

TABLE 3 (Continued)

Sno	Project name	Country	Date online	Technology		Announced size	Normalized capacity		
				Electrolyzer type	Type of renewable		MWel	Nm^3 H_2/h	kt H_2/y
					Onshore wind				
23	Chongli wind-solar Hydrogen Project–first phase	CHN	2021	PEM	Others/Various	1.7 t H2/d	2	385	0.3
24	WindGas Hamburg-Reitbrook	DEU	2015	PEM	Onshore wind	1.5 MW	1.5	288	0.2
25	Leuchtturmprojekt Power-to-Gas Baden-Württemberg	DEU	2020	PEM	Hydropower	1.3 MW	1.3	250	0.2
26	Wyhlen hydroelectric power plant	DEU	2020	ALK	Hydropower	1.3 MW	1.3	283	0.2
27	Hydrogen Park South Australia–HyPSA	AUS	2021	PEM	Others/Various	1.25 MW	1.25	240	0.2
28	eFarm (5 production sites in North Frisia)	DEU	2020	PEM	Onshore wind	1.125 MW	1.13	216	0.2
29	Hydrogen plant–Orkney Islands–BIG HIT 2n phase	GBR	2019	PEM	Onshore wind	1 MW	1	192	0.1
30	Windgas Haurup, 2nd phase	DEU	2020	PEM	Onshore wind	1 MW	1	192	0.1
31	RH2 Grapzow, Mecklenburg Vorpommern	DEU	2015	ALK	Onshore wind	1 MW–200 m^3 H_2/h	1	217	0.2
32	Sealhyfe	FRA	2022	PEM	Offshore wind	1 MW, 400 kg H_2/d	1	192	0.1

4 | GEOPOLITICAL IMPLICATIONS

As hydrogen becomes crucial for achieving net-zero emissions, countries balance collaboration with autonomy in their strategies. The EU, the United States, Japan, South Korea, and China have set ambitious emission reduction targets, relying on hydrogen to transform energy-intensive industries. Different nations focus on various innovation pathways, such as hydrogen derivatives for shipping in Japan and Korea, hydrogen-powered trains and planes in the EU, and methane pyrolysis in the United States.

The green hydrogen revolution has significant geopolitical implications for G20 nations, reshaping global power dynamics and substantially impacting present geopolitical dynamics via shifting energy reliances and trade flows. Green hydrogen can be produced in several G20 countries, reducing dependence on traditional oil and gas exporters such as Saudi Arabia and Russia and potentially lowering geopolitical tensions linked with existing energy supply channels. This transition enables G20 members with vast renewable resources, such as Australia and Brazil, based on the present situation, to emerge as significant hydrogen producers.

Traditional fossil fuel exports of the G20 countries face the difficulty of stranded assets. Still, they can use green hydrogen to diversify their economies and stay competitive in the global energy market. However, building global hydrogen supply chains presents new geopolitical concerns, such as conflicts, piracy, terrorism, and regional instability, which must be managed to ensure reliable hydrogen supplies (Sprenger et al., 2023). Major demand centers within the G20, particularly the EU, and Japan, play an essential role in defining the global hydrogen economy, as seen by Australia's delivery of its first liquid hydrogen to Japan in early 2020, indicating a demand for liquid hydrogen (Van de Graaf et al., 2020). The EU's investment in hydrogen projects and significant funding influence global trade patterns and standards. Additionally, new trade routes for hydrogen and its derivatives will differ from current fossil fuel

pathways, potentially enhancing the geopolitical significance of G20 regions like Argentina and Indonesia while diminishing the influence of some Middle Eastern countries.

Despite aspirations for energy independence, reliance on hydrogen imports remains inevitable, highlighting the need for diversified supply chains to mitigate geopolitical risks. Managing dependencies across sectors and establishing global hydrogen governance, such as a "Hydrogen Alliance," is essential to reduce geopolitical risks and promote collaboration. Hydrogen Realignment, Hydrogen (In)Dependence, and Hydrogen Imperialism—These scenarios explore different geopolitical outcomes based on how countries manage their hydrogen strategies and dependencies. The Hydrogen Imperialism scenario, for instance, depicts aggressive hydrogen economy advancements leading to geopolitical tensions and market rivalries (Pepe et al., 2023).

When nations began to use hydrogen as fuel, the coalition between forms was based on the supply of raw materials required for green hydrogen, such as platinum, cobalt, nickel, lithium, and other rare earth metals. Water and electricity are almost available in all the G20 nations as they have coastal areas to most of the nations (Tleubergenova et al., 2023). Eikeng et al. (2024) have classified the required materials for green hydrogen production and storage and nations with reserves to meet future demand. According to the authors, Canada, South Africa, China, and Russia produce these crucial elements more diversely, making them essential to the stakeholders' supply chain. The supply of raw materials to fabricate electrolyzer from various nations has been represented in Fig.2.

In 2010, China accounted for 80% of the rare earth elements market share, which has dropped to 60% by 2021 due to restrictions on selling these resources to Japan, forcing the rest of the world to diversify their supply chain (Yang, 2024). If the hydrogen production business increases rapidly, the supply of raw materials for the anticipated expansion will be insufficient and challenging. China is the largest producer of the critical raw materials required for green hydrogen production. According to IEA and IRENA forecasts (IEA, 2021a; IRENA, 2022), there will be a supply

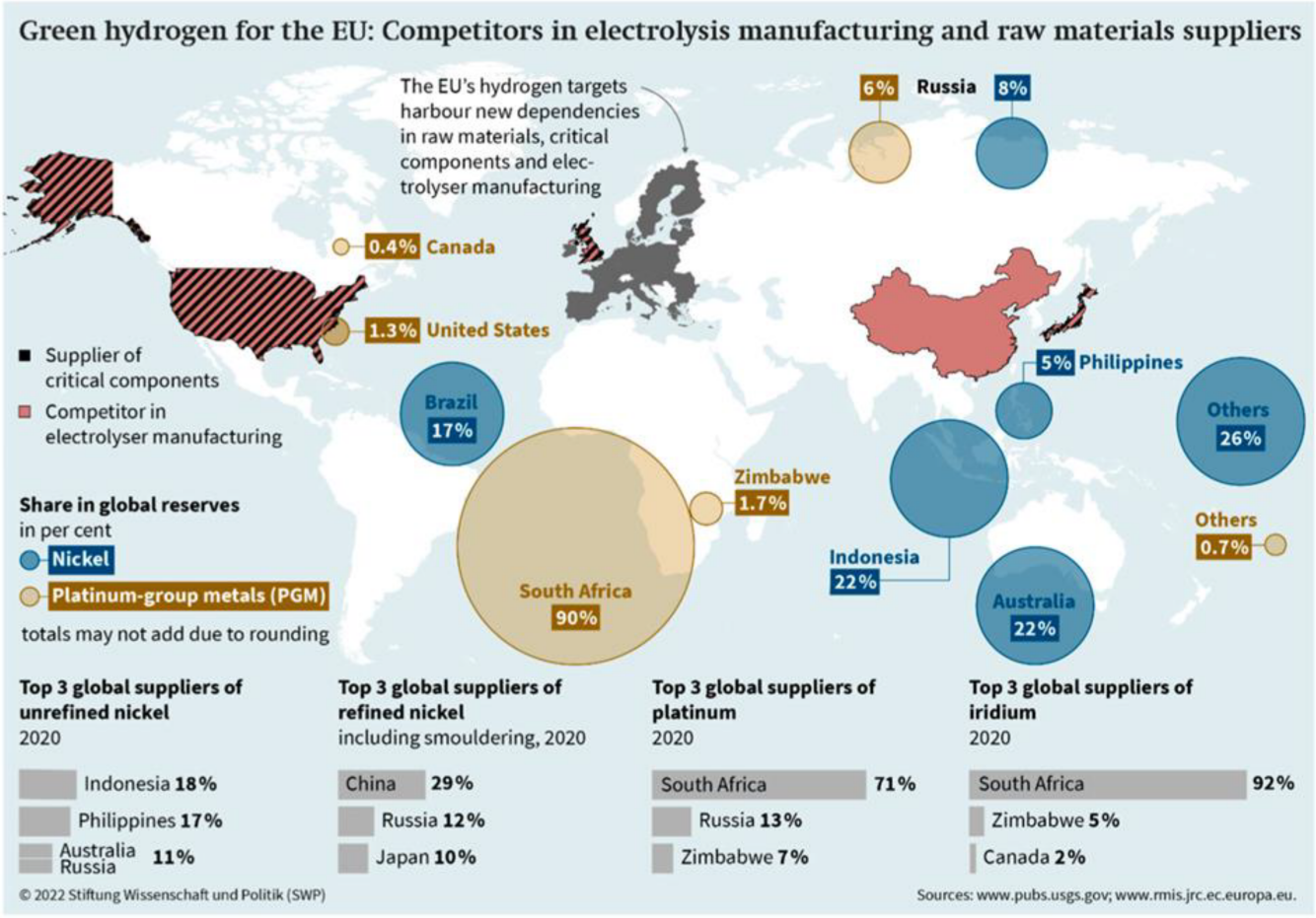

FIGURE 2 Competitors in electrolyzers manufacturing and raw materials suppliers for green H_2 production of the EU. Reproduced with permission from Sá and Helena (2024).

and demand mismatch in the future, resulting in raw material shortages and price increases owing to rivalry with other renewable energy sectors. Even green hydrogen requires solar and wind energy for a seamless transition; yet, raw materials needed for solar and wind expansion, such as nickel and copper, will be restricted, affecting the deployment of electrolyzers. The countries that produce the most raw materials have the exclusive right to impose their nation's policy during sale and might refuse if the importing nation violates their policies. Critical rare material dependence in the hydrogen economy poses several challenging problems, including scarce supply, environmental impact, and geopolitical implications. Overcoming these challenges requires a diverse approach that involves creativity, research, and long-term legislative frameworks. The future of the hydrogen economy will likely focus on increasing efficiency, lowering prices, and minimizing environmental consequences, all of which will help to develop a sustainable and resilient hydrogen economy (Eikeng et al., 2024). The 2020s could see a competitive race for technological leadership in hydrogen, driven by cost reductions from learning and infrastructure scaling. This era presents opportunities in equipment manufacturing, likely to capture significant value in the future (IRENA, 2022).

5 | CHALLENGES AND OPPORTUNITIES

The main difficulty for all G20 countries is to generate demand, produce enormous amounts of hydrogen at cheaper costs, handle the gas, and choose where to use it. The standard SMR technique is less expensive than the electrolysis process, but it necessitates using a CCUS unit, which incurs additional costs due to the technology's infancy. Green hydrogen requires renewable energy and electrolyzers, which are capital-intensive. Handling hydrogen is another challenge because it requires deciding whether to use pure hydrogen or transform it into numerous compounds, each with benefits and logistical challenges. Application options span from industrial to a larger hydrogen-based civilization, with efficiency and potential lock-in hazards influencing selections. Investment in infrastructure is risky without specific supply and demand, complicating the transition (Van de Graaf et al., 2020).

The amount of water required to produce hydrogen using electrolysis and how it compares to other sectors. It takes 20.5 billion cubic meters of freshwater to produce 2.3 Gt of hydrogen each year, which accounts for only 1.5 ppm of Earth's freshwater. This amount of water is significantly less than that used in fossil fuel energy production, electricity generation, and agriculture. Agriculture employs more than 50 times as much water as the expected hydrogen economy. The low water usage for hydrogen production implies it is a viable and sustainable alternative to present energy sources. Reverse osmosis (RO) converts seawater into freshwater for electrolysis. RO is energy-efficient, adding minimal cost to hydrogen production. Producing 2.3 Gt of hydrogen would require 41 billion m^3 of seawater annually, a negligible impact on global seawater resources (Beswick et al., 2021).

Including social sciences in the study of green hydrogen, stating that understanding public opinion, socio-environmental consequences, and social acceptance is critical for the effective implementation of green hydrogen technology as there are a lot of misconceptions about the water used for electrolysis and the safety of hydrogen. Vallejos-Romero et al.'s (2023) papers call for further interdisciplinary study to address these social dimensions and develop public policies that promote social acceptability while mitigating any socio-environmental dangers. It also implies that involving several stakeholders, including the general public, in decision-making processes can boost the legitimacy and efficacy of green hydrogen projects. The potential for growing the green hydrogen economy, including cost efficiency, innovation, sector connectivity, and reduced grid reliance. As hydrogen technology advances and economies of scale are reached, the cost viability of Power-to-Hydrogen-to-Power (P2H2P) systems will increase dramatically. R&D is critical to this process, boosting electrolysis efficiency, advancing cost-effective compression and liquefaction technologies, and creating innovative storage materials and ways to minimize storage and distribution costs.

Furthermore, collaborating between academia and businesses to reuse existing natural gas pipes for hydrogen transportation can help lower infrastructure costs. Integrating hydrogen into many sectors, such as transportation and manufacturing, can improve energy system efficiency and sustainability. This method can assist in decarbonizing numerous sectors, reduce dependency on fossil fuels, and enhance energy security. Furthermore, adopting hydrogen as an energy storage solution can improve grid stability and reliability, making renewable energy sources more competitive. When paired with supportive policies and technological breakthroughs, these opportunities can expedite the deployment of hydrogen energy systems, facilitating the worldwide transition to zero-emission economies and meeting sustainability targets (Risco-Bravo et al., 2024).

6 | CONCLUSION

In conclusion, the G20 nations are investing in hydrogen from electrolysis, aiming to decarbonize sectors like aviation, shipping, and steelmaking. These nations recognize that global energy trade will shift from fossil fuels to hydrogen, leading to significant geopolitical and geo-economic changes. The EU, especially Germany, prioritizes green hydrogen, while other G20 countries also consider blue and nuclear-based hydrogen. Geopolitical roles vary, with some nations poised to be exporters and others importers of hydrogen. Commitment to sustainable hydrogen production differs, reflecting national priorities and resources.

When we compared G20 nations polices based on their economic status including their oil importing or exporting capabilities with green hydrogen policies, we observe that the nations from categories 1 and 2, are committed to energy transition towards NetZero emissions as seen in Table 1 through policies, targets, and investments; and are ready to slowly phase down the fossil fuels based on the targets set by the respective nations. The nations from categories 3 and 4 are also committed to energy transition, as these nations are still developing with moderate to huge energy demands based on the population, these nations are increasing the renewable and fossil fuel based infrastructure simultaneously to compete the economic growth with the developed nations.

Overall, the G20 nations are willing to finance renewable energy and gradually phase out fossil fuels in most of the sectors. They are also committed to raising demand for hydrogen and lowering green hydrogen prices. On the other hand, net oil-importing countries look forward to transitioning to green hydrogen since it will allow them to minimize their foreign exchange spending amid price shocks in an inescapable geopolitical situation. Current oil exporters are eager to capitalize on the early hydrogen markets by delivering gray/blue hydrogen before green hydrogen becomes mandatory under national legislation. As renewable energy prices and critical raw materials are also essential in economically viable hydrogen, nations need to kickstart hydrogen and its value chain through low-carbon emissions-based hydrogen production methods from fossil fuels as they are financially feasible for mass production. Once the hydrogen has started, it needs to be slowly transitioned toward green hydrogen to have the same economic viability.

Governments worldwide need to carefully manage their raw material supply chain, as geopolitical power can move towards the nation with the supply of rare-earth minerals essential for the energy transition, which can lead to price volatility, trade wars, sale embargo, and supply disruptions (Ilankoon et al., 2022). As previously discussed, the energy transition to low-emission fuels has begun and will require a concerted push from legislation and investments in RE. The green hydrogen revolution has already started in almost every industry to decarbonize; the G20 nations are also entirely committed to promoting hydrogen to be energy independent and avoid foreign exchange expenditure on oil amid the geopolitical crisis. To alleviate the burden of capital investment, the G20 should focus on balancing the prices of fossil fuels and hydrogen and green hydrogen.

The G20 nations can be essential in building lead markets for key hydrogen value chain components required for scaling up green hydrogen. With widespread agreement among G20 members, this can include green hydrogen, green ammonia, and other hydrogen derivatives. It also provides funding for the construction of electrolyzers, transportation infrastructure, hydrogen pipelines, and facilities for shipping hydrogen and its derivatives, such as ports and ships. To combat climate change and facilitate the transition to renewable energy, all G20 nations collaborate by voting for equivalent hydrogen economy standards, sharing knowledge and resources, and investing in poorer countries to preserve the globe from climate change.

The future of the green hydrogen economy and the energy transition is partially based on geopolitical stability, cooperation, and critical resource sharing. The other part of the energy transition is based on the policies of the G20 nations, where nations need to focus on subsidizing RE technologies rather than crude oil, creating demand for the H_2, which in turn creates demand for the infrastructure and value chain products which enables promoting to decarbonize various industries such as automobile, oil and gas, steel, fertilizer, and power sector and will fulfill the goal of the Paris Agreement.

AUTHOR CONTRIBUTIONS

Hari Pavan Sriram Yalamati: Conceptualization (equal); data curation (equal); investigation (equal); methodology (equal); writing – original draft (equal). **Rakesh Kumar Vij:** Supervision (supporting). **Rohit Srivastava:** Conceptualization (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); supervision (lead); validation (lead); visualization (lead).

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The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Yes we agree.

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